
The Antikythera Mechanism reconsidered*

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The Antikythera Mechanism, the world's oldest known geared mechanism, became widely known through the work of Derek Price who, concluding that its dials yielded astronomical and calendrical information, called it a 'calendar computer'. Price rightly drew attention to its importance as direct evidence for a high level of mechanical accomplishment in ancient times, but his account of the instrument itself is deficient. I have developed a new reconstruction on the basis of an independent survey of the original, drawing on my knowledge of early mechanism and of the history of craft techniques, and on my experience as a practical mechanic. This reconstruction follows the observed detail far more closely than does Price's. It displays somewhat different astronomical information, according closely with the contemporary literary evidence of interest in the making of planetaria. The main features of the new reconstruction, previously described elsewhere in a series of papers, are here brought together so as to convey a better impression of the whole. A model, made to the same scale as the original, demonstrates that the reconstruction is workable.

In 1900, just off the small Greek island of Antikythera in the Western Aegean, sponge-divers discovered statues on the sea bed at a depth variously reported as between about forty-three and fifty-five metres. These were the largest items in a cargo of mixed luxury goods from a shipwreck which has subsequently been dated, by several independent studies, to the early decades of the first century BC.¹ The Greek government employed the divers to recover what they could, and the material was taken to the National Museum in Athens where much of it may now be seen on display.

* Note added 29 November 2006: This paper was submitted on 2 September 2006 and accepted for publication on 26 October 2006. Since then the Antikythera Mechanism Research Project Group has published interesting findings (T. Freeth *et al.*: 'Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism', *Nature*, 2006, **444**, 587–591). Their independent survey has included study of the newly discovered fragment F, a part of the lower back dial which was not available to me. Their reading of the inscriptions on this dial reveals that the function displayed on it was the eclipse cycle of 223 synodic months, distributed around the four-turn spiral scale. (As eclipses of the Sun are rare events, the engraved sequence may, in principle, afford means for dating the Mechanism.) One revolution of the pointer thus represented $(223 \div 4)$ synodic months, not one draconitic month as I have suggested. The Group offers a modification of my gear train which achieves this function and also incorporates exactly those mechanical features that I characterised as having probably been made redundant by alteration of the instrument. The satisfactory way in which the Group's suggestions for these parts fall in with my own observations of the artefact itself, and remove residual difficulties with my reconstruction, lead me to believe that they are correct. I have no hesitation either in adopting the Group's revisions of the function of the lower back dial and of the internal mechanism or in withdrawing statements concerning these features that conflict with them. The changes, though important, are physically quite slight, and do not affect my arguments for other significant features of my reconstruction. I stand by the conclusions of my paper.

The considerable bulk of this 'Antikythera treasure' included spectacular artefacts which drew much attention. Understandably, therefore, the small pieces of the fragmentary instrument which forms the subject of the present paper were examined closely only some months later, when engraved lettering was noticed on them. The inscriptions showed that the instrument's purpose had been astronomical, and traces of toothed wheels and graduated dials could be seen, but the artefact's enormous importance, as the world's earliest known geared mechanism, was recognised only later.

The first official description of what we now call the Antikythera Mechanism is found in a museum publication of 1903.² Four distinct fragments, designated A, B, Γ and Δ (A, B, C and D in later literature), were described and illustrated by photographs and a few line-drawings. Further fragments, E and F, have been identified more recently within the museum's store. Some flakes of what had been a separate plate, detached from fragment C during cleaning, have been reassembled to form what is now called fragment G, and many further similar flakes from fragments A, B and C, mostly very small, are numbered for reference.

The nature of the fragments is such that much of their detail remains hidden from direct view, even after cleaning. Radiography, carried out in the early 1970s by Charalambos Karakalos, revealed much more and encouraged Derek de Solla Price to attempt a complete description and reconstruction of the instrument, in a paper which has become well known.³

Price opened this paper with an account of the finding of the wreck and recovery of the cargo, and with the history of studies of the fragments prior to his own; and concluded with a masterly essay on the historical significance of the instrument. Between these sections, he devoted half the paper to a description of the evidence available to him (mainly of fragments A, B and C and the assembly now called fragment G) and his reconstruction based upon it.

Price described an instrument of bronze, contained in a wooden case. Three dial displays, one on the 'front' and two on the 'back', were interconnected by internal gearing and driven forward together by the rotation of a single input shaft.⁴ Two pointers on the front showed the mean places in the Zodiac of the Sun and Moon (the first also showing the date), and their motion was combined in an epicyclic differential gear to drive a display of the synodic month on the back.⁵ Simpler gearing to the other back dial displayed supplementary information. Further bronze 'door plates', the surviving pieces of which are densely engraved with writing which appears to have an astronomical significance, lay over the front and rear dials. Price identified no specific purpose for the instrument, but called it a 'calendar computer'.

Numerous models have been made, based more or less closely on Price's account. I have shown that Price's reconstruction is fundamentally incorrect.⁶ Therefore none of these models, however well or badly made, possesses any basis in historical reality; nor can any of them offer any true insight into the design, construction or function of the original.

Classical literature includes passages that refer to instruments showing the places of the Sun, Moon and planets. Price presented several in translation, the earliest written by Cicero (Marcus Tullius Cicero, 106–43BC), during whose lifetime the Antikythera ship was lost. It had been usual to suppose that ancient attainments in mechanical technology were only modest, and that these instruments must have been simpler than the authors implied; but

Price suggested that the Antikythera Mechanism, with its dozens of small gear wheels, compels us to revise our perception of their probable degree of technical development. His paper was recognised as an important contribution,⁷ but with hindsight we see that few readers can have taken the time to appraise the detailed argument by which Price arrived at his reconstruction.

A NEW SURVEY OF THE ARTEFACT

While working on a later Greek geared instrument for which the Antikythera Mechanism provided important comparison material,⁸ I was compelled to re-read Price's paper with care and began to notice objections to his account. Price contradicted himself, and contradicted or ignored detail that could be seen in the illustrations; he appealed to arguments concerning the design and execution of mechanic's work that carried little or no conviction, or even made no sense at all; and his reconstruction was both bizarre and incomplete. What one sees depends on what one's training and experience predispose one to see. I became convinced that by bringing to bear powers of observation developed as a museum curator in the study of intricate mechanism and craft techniques, together with the practical insights of a skilled workman, I might make a worthwhile contribution to the study of the Antikythera Mechanism. In due course I arranged to examine the original fragments myself, in collaboration with the late Allan Bromley.⁹ It became clear immediately that Price really was mistaken in important respects; and so we made a wholly independent survey of every detail, amassing data by direct examination and measurement, photography and radiography.¹⁰

Since Price had clearly faced difficulty in determining the spatial relationship between closely spaced features seen in radiographs, I devised apparatus to adapt standard X-ray equipment for linear tomography.¹¹ This technique allows one to prepare sets of plates which, once collated, enable one to plot the depths of features within the object.¹² We achieved a radiographic resolution considerably better than 0.1 millimetres. This is of the same order of magnitude as both the working clearances in the instrument and the degree of fine adjustment that a workman might have achieved using simple tools and the naked eye. It is an order of magnitude smaller than the ruling dimension of the thinnest components. At this resolution the definition of the image appeared to be limited not by the imaging technique but by the ruined state of the artefact.

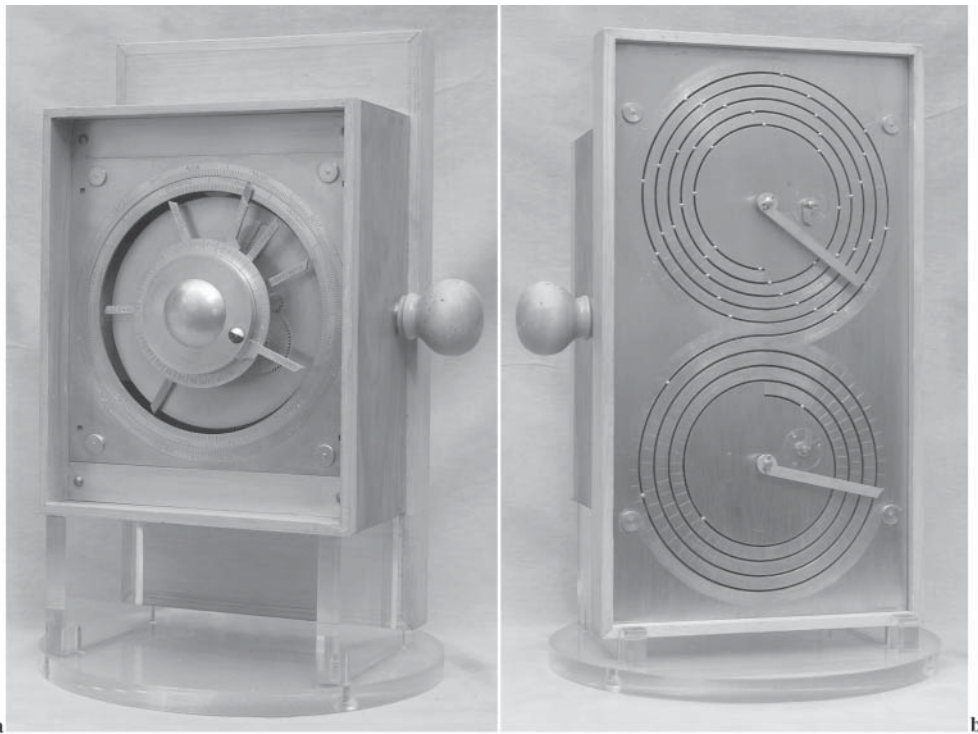
Our large bulk of research material demanded painstaking analysis, for which Bromley removed it all to Sydney. His attempt was however cut short by the onset of a serious and ultimately fatal illness. After some delay, most of the material was recovered and work on it resumed in London. By this time the web of Price's reconstruction had unravelled almost completely, but it proved harder to establish a new scheme that both accorded with observation and possessed a satisfactory internal logic. That has now been achieved, as is described step by step in the series of papers listed in the Bibliography below.

There remains a problem in publishing the radiographs which comprise the most important part of our research material. The range of image-density in a successful radiograph may be enormous, far beyond that which can be achieved in printing on paper. The problem is exacerbated where, as here, the variation in radiographic density of the artefact is itself very large. There is no simple way of publishing many of our images without so

much loss of quality as to make them practically meaningless. With linear tomographic images the problem is still worse, because they necessarily have much visual 'noise' and rather low contrast, and can in general be understood only by an experienced observer. These plane images could be made clearer by the application of relatively simple techniques in information engineering; and, using more elaborate procedures, they could be reconstituted as a virtual three-dimensional image. Easily intelligible images are however now obtained as a more direct outcome of the use of modern scanning equipment.¹³

It must be said that the poor state and limited extent of the original fragments is such that images of them, however good, can never alone lead to an exact description of the whole of the original instrument; but our radiography has yielded enough clear information about the general mechanical arrangement of the fragments for me to have some confidence in publishing a reconstruction of the instrument's arrangement and function. I have illustrated it and demonstrated its practicability by constructing a full-size working model (Fig. 1).

The basis of the resulting reconstruction is a new survey of the arrangement of the gear wheels, together with new estimates of the numbers of their teeth. Both the method and the results of the survey have been published.¹⁴ A very great mass of further mechanical detail was obtained, which is also embodied in the model. The order in which the elements of my new reconstruction were actually established was a matter of expediency. They are described here in a different order more suited to a logical exposition, beginning with what is seen in the original fragments and working outward.



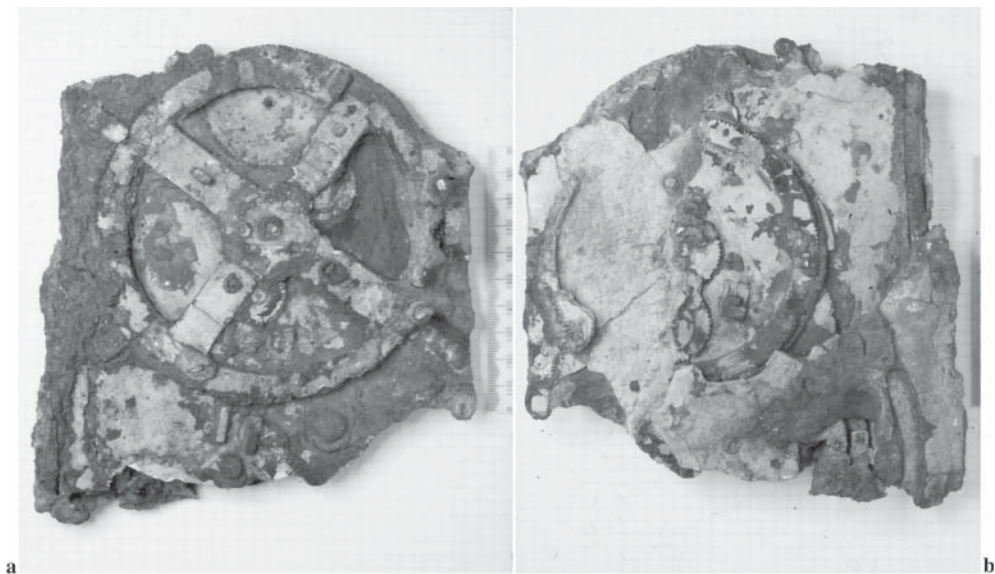
1 The Antikythera Mechanism, reconstruction by M. T. Wright (2005): **a** front view, **b** back view

THE ORIGINAL FRAGMENTS

All the surviving metallic parts seem to have been made of bronze, mostly from quite thin sheet, between one and two millimetres thick. Many parts appear to be almost wholly converted to corrosion products, but exquisite surface detail is retained in many places. The possibility exists that there were components of iron or steel, but these would have perished preferentially through electrochemical action.

Most of the surviving internal mechanism, the remains of some twenty-seven small gear wheels ranging from about nine to about 130 millimetres in diameter and arranged in compound trains on twelve separate axes, is found in the largest piece, fragment A (Fig. 2). The greatest dimension of the fragment itself is about 217 millimetres. Most of the wheels were fitted to arbors which ran in pivot-holes made in a frame plate.¹⁵ Enough of the outline of the frame plate – one straight edge and one right-angled corner – survives to suggest that the plate was rectangular. A portion of a dial plate (I follow Price in calling it the back dial) lies roughly parallel to the frame plate. The remains of a wooden batten, presumably one of a pair that separated the dial from the frame plate, lies between them, close to the preserved edge of the frame plate. There are traces of two further pieces of wood, just beyond the side and bottom edges of the frame plate, that met at the corner in a mitred joint.

Fragment B, with greatest dimension about 124 millimetres (Fig. 3), comprises mainly a further part of the back dial plate with two broken arbors and the trace of one further wheel. It fits against fragment A; while fragment E, with greatest dimension about 64 millimetres, includes a further small piece of the dial and fits between A and B (Fig. 4). Together they afford a glimpse of the arrangement of the dial: two systems with (in their fragmentary state) the superficial appearance of sets of detached rings, one above the other, on a rectangular plate roughly twice as high as it was wide. The newly discovered fragment F includes a further piece of this back dial plate, with traces of woodwork forming a mitred joint at the corner of the plate.



2 The Antikythera Mechanism, original fragment A: *a* front view, *b* back view



3 The Antikythera Mechanism, original fragment B: *a* outside, *b* inside

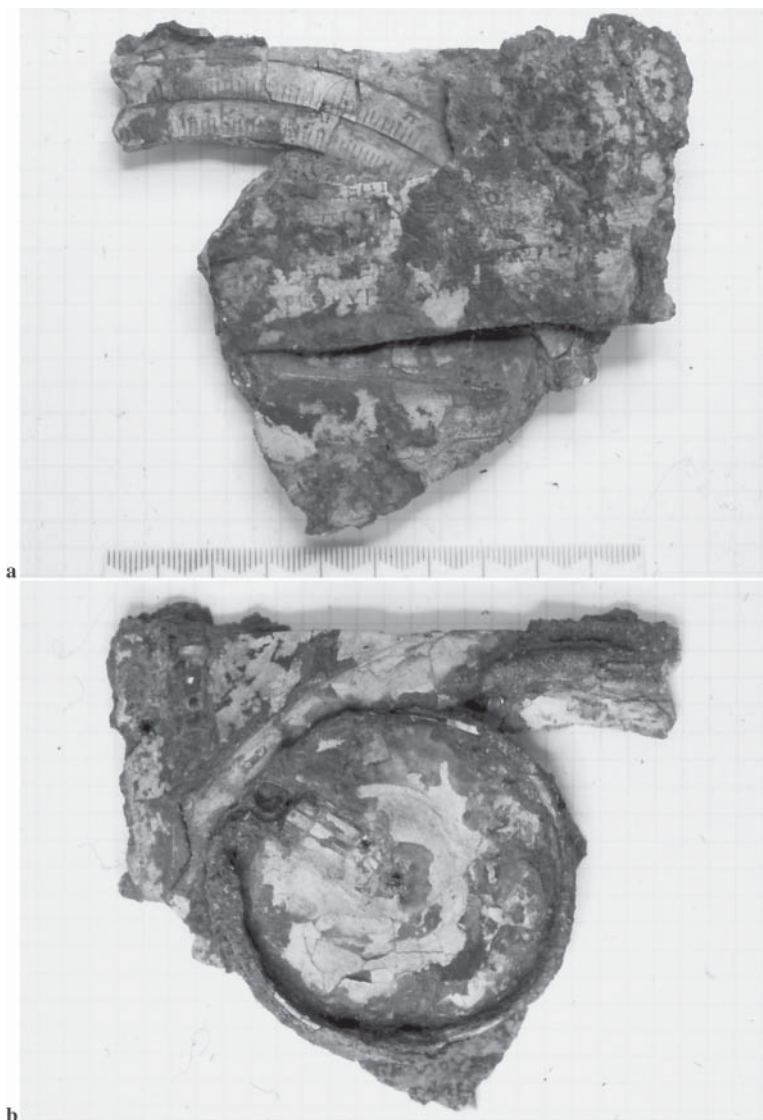
Fragment C has greatest dimension about 120 millimetres (Fig. 5). The largest single component within it is a corner of the dial from the opposite (front) face, which formed the principal display. This square dial bore two concentric rings of graduations: one, engraved on the plate immediately outside a large central circular opening, was divided into 360 parts (degrees), in groups of thirty engraved with the names of the twelve signs of the Zodiac; the other, divided into 365 parts (days), in groups of thirty engraved with the names of the months of the year according to the Egyptian calendar,¹⁶ was laid out on a detached ring that lay flush, in a circular sink. Near the corner of the dial is a small sliding bolt worked by a thumb-button, which served to hold the dial in place. Behind this piece of dial, cemented to it by corrosion products, lies a circular component containing the remains of a tiny contrate wheel.¹⁷ Price identified this component tentatively as a hand-knob, but it actually formed an important part of the central feature of the front dial: a device for displaying the phase of the Moon.¹⁸

All these fragments include traces of the bronze plates that lay over the dials, densely inscribed with lettering. Some pieces of them have been removed from the main fragments during cleaning and conservation, and some have been reassembled separately to form what is now termed fragment G. The remaining detached pieces, mostly very small flakes, are now designated by numbers. I accepted the help of an eminent epigraphist in trying to extend the published readings of the lettering, and so made no serious attempt to read it myself;¹⁹ but I did note that Price and his collaborators were unduly tentative in recording as ‘uncertain’ many letters that I found clearly legible. Perhaps they were obliged to work under difficult conditions.



4 The Antikythera Mechanism, original fragments A, B and E posed together

Fragment D comprises two wheels, lying together with the trace of a thin plain plate between them. The two wheels are not quite concentric, and the arbor on which they must have been mounted is absent. There is no place for them anywhere in the other extant fragments and their original purpose cannot be determined. Probably they formed part of one of the several trains that are conjecturally restored in my reconstruction.



5 The Antikythera Mechanism, original fragment C: *a* outside, *b* inside

GENERAL ARRANGEMENT OF THE INSTRUMENT

The whole movement is built around a reverted train,²⁰ which connects the large wheel on one face of fragment A (Fig. 2*a*) and the arbor that passes up through its central boss. As Price showed, the velocity ratio of this train (19:254) has an astronomical significance: in nineteen years there are, to a good approximation, 235 synodic months and hence 254 sidereal or tropical months.²¹ Therefore the rotation of the wheel and of the central arbor drove pointers showing respectively the apparent motions of the Sun and Moon in longitude; but in an important correction to Price's scheme, the train takes in one more arbor

than he thought, and so the wheel and arbor rotate in the same sense.²² Supposing that they rotated in opposite senses, Price added a reversing wheel, lying over the large wheel. This extra wheel is now discarded; indeed, examination of the original shows that it could never have been fitted. Without it, the way lies open to the more elaborate reconstruction of the front dial described below.

The Moon pointer incorporated the Moon-phase device that is partially preserved in fragment C (Fig. 5); and the Sun and Moon pointers, and perhaps others (see below), were read against the Zodiac scale of the dial, part of which is preserved in fragment C also, which must have been positioned over fragment A, concentric with its central axis. Price seemed uncertain as to whether there was a direct join between fragments A and C.²³ In fact there is none, and so both the correct orientation of the dial and its separation from fragment A are indeterminate.

The front dial display also included an indication of the day of the year. According to the Egyptian calendar the dates of the equinox and solstices changed by one day every fourth year. This explains the provision of the moveable calendar ring.

Fragment A includes much of two further gear trains, leading away from different points in the reverted train to carry motion to the two dials on the back of the instrument (Fig. 4). The train to the upper back dial is a straightforward fixed-axis train. That to the lower back dial includes an epicyclic assembly (Fig. 2*b*), which Price identified, incorrectly, as a differential gear. Each back dial system includes a small offset subsidiary dial on which a small pointer rotated more slowly than the principal pointer at the centre.

While the batten between the frame plate and the back dial may have been merely a spacer, the further woodwork beyond the edge of the frame plate is interpreted as the remnant of a case embracing the plate and enclosing the mechanism mounted on it. The front dial would have fitted neatly to a case of this size. The piece of the back dial remaining in fragment A overhangs the extant woodwork. Therefore the case must have been stepped out to embrace the rectangular back dial plate, as the trace of a further mitred joint at the corner of fragment F confirms. My model (Fig. 1) shows the general arrangement, but the correction of dimensions and some minor details may be called for in the light of an examination of fragment F.²⁴

Although Price called the plates that lay over the dials ‘door plates’, there is no evidence that they were jointed to the casework. I have modelled them as detached covers which drop onto rims of woodwork projecting beyond the dials. They serve the practical purposes of allowing the user to rest the instrument on one face while working it, and of forming a closed protective box when it is carried around. The surviving pieces of the originals were densely inscribed with lettering. The legible texts, as reported by Price,²⁵ are very fragmentary, but they appear to constitute data allowing the instrument to be set to the correct date and some sort of account of astronomical phenomena and period-relations associated with what was shown on the dials. These plates are not shown in my photographs.

The mechanism was driven by turning a contrate wheel, preserved in fragment A. The wheel has a large rectangular central hole which I interpret as a socket designed to receive a tongue formed on a wooden hand knob which, in my model, is inserted into a socket in the side of the case. The arrangement is comparable to the coupling between the tuning pegs of a lyre and the key used for adjusting them, but inverted.

THE BACK DIALS AND THEIR GEAR TRAINS

The upper and lower back dials have spiral scales,²⁶ the lower having four turns and the upper five. Each scale is flanked by a spiral slot cut right through the plate, perhaps to allow loosely riveted captive beads to be pushed freely along the scales as moveable markers (Fig. 1*b*). The model illustrates the possibility that the outer volutes of the two spiral systems may have been joined, to form a single continuous S-shaped curve.

The establishment of the correct spatial relationship between fragments A and B, and of the layout of the dials, led to the reconstruction of the display function of the upper back dial and the restoration of the train leading to its centre.²⁷ Each rotation of the main pointer represents 3.8 years: that is, forty-seven synodic months according to the approximation which – as noted above – is built into the central reverted train. Each turn of the scale was divided into forty-seven equal parts, and so the full five-turn spiral scale represents 235 synodic months, or nineteen years.

The subsidiary dial appears to have been divided into four quadrants marked with characters for the numbers nineteen, thirty-eight, fifty-seven and seventy-six. The gear train driving its pointer, lost at the upper edge of fragment B, is restored accordingly. The small pointer keeps a count of the nineteen-year cycles indicated by the principal display. Each full turn of the pointer signifies the passage of seventy-six years: an interval, known as the Kallippic Period,²⁸ that was used by astronomers in time-reckoning.²⁹

This display might have been used in comparing the solar Egyptian calendar, which was used by astronomers, and which is engraved on the front dial, with any of the lunar or luni-solar calendars otherwise used in Hellenistic society before (and, in some cases, for many years following) the introduction of the Julian calendar in 44BC. It also served as a counter in establishing the intervals of time between astronomical indications shown on the other dials by different settings of the instrument. The latter function, especially, makes good sense in relation to the reconstruction of the front dial discussed below. The user could move beads along the spiral slot to mark significant calendrical or astronomical events. For example, the 235-month scale is long enough to contain rather more than one so-called ‘Saros’ eclipse cycle of 223 synodic months.³⁰ Each of the individual eclipse-possibilities of the cycle might be marked by the placing of a bead. Reference to the 223-month cycle, and to the nineteen- and seventy-six-year cycles, is found inscribed on one of the fragments of the back ‘door plate’.³¹

Price was mistaken in identifying the epicyclic arrangement in the train to the lower back dial as a differential gear; in reality it appears to have had only one input, not two,³² so that the assembly would have served to modify slightly the velocity ratio of the fixed-axis section of the train. Its presence raises interesting questions as to both the designer’s intention and his design procedure, but any attempt to answer them is frustrated by the severe mutilation of most of the wheels. I conjecture that each revolution of the main pointer at the centre of the dial was intended to represent one ‘draconitic month’, approximately 27¼ days. This is the mean period between successive passages of the Moon past either of its nodes, the points at which its apparent path intersects that of the Sun.³³ Eclipses can occur only when the Moon is near a node, and so this display was intended for predicting when they might occur. The spiral scale was divided into 218 equal parts, 54½ approximate half-days per turn. The significance of its four turns is that, by this

reckoning, the full scale contains a whole number of days (109). The half-day divisions might have been used in attempting to judge whether a predicted eclipse would be visible. As on the upper dial, the spiral slot allows the placing of markers at will. The subsidiary pointer rotates once in twelve turns of the principal one, moving over a circle marked to indicate the passage of four, eight and twelve draconitic months. It enables the user to keep count of the turns of the main pointer.

THE FRONT DIAL

All the features of the new reconstruction described so far follow from detail found in the original fragments; and so too do some elements of the front dial. The concentric mobiles in fragment A, the large wheel and central arbor (Fig. 2*a*), gave motion to pointers showing the places of the Sun and Moon on the Zodiac scale of fragment C (Fig. 5*a*) and the date on its calendar scale. To these is added the display of the phase of the Moon, reconstructed from the circular component within fragment C (Fig. 5*b*).³⁴ Beyond this, there is clear evidence that the large wheel in fragment A carried epicyclic gearing, indicating that the front dial display was more elaborate still. However, this hard evidence cannot be explained without some degree of conjectural restoration, and so the further features of any reconstruction remain debatable. I have shown that it is possible to reconstruct the front dial so as to include indications of the places of all five planets.³⁵ The restored epicyclic mechanism serves to model the epicyclic theory that had been introduced into Hellenistic astronomy late in the third century BC.

The possible function of the restored mechanism is limited by its mechanical and astronomical context. One turn of the wheel represented one year, so the choice is restricted to the modelling of phenomena with a tropical period of one year: the observed motion of the Sun (as distinct from its mean motion, represented by that of the wheel itself),³⁶ or the motion of one of the two 'inferior' planets, Mercury and Venus,³⁷ which are always seen close to the Sun. A simple epicyclic model of any one of these three functions might account for the evidence. However, the wheel representing the epicycle for Venus must be large in relation to the platform on which it is mounted, and large forces are generated in the associated components. The need to construct the assembly to an adequate scale provides a reason for the otherwise unexplained large size of the wheel, which suggests that this planet was indeed included. The designer's interest in Venus is also shown by a fragmentary inscription: '... της αφοδίτης ...', '... of Venus ...'.³⁸ Seeing, however, that none of the five planets then known was accorded the special status that would justify individual treatment to the exclusion of the others, it is improbable that, having adopted a mechanical arrangement that could replicate the motion of the planets, the designer would have been content to model only one. It seems more likely that he would have been interested in repeating the arrangement several times over so as to develop a full and consistent display of the motions of all the planets.

I have accordingly developed a conjectural reconstruction that is more elaborate than the physical evidence actually demands, but which is called for, at the very least as an exploration of what is possible, by the general character of the instrument, its observed detail, and the contemporary interest in models showing the motion of the planets that is so clearly expressed by ancient authors. In this reconstruction, the front dial shows the

places of all five planets known in antiquity, as well as those of the Sun and Moon; but the elaboration is achieved by simple means, using only elements of the mechanical repertoire found elsewhere within the extant fragments. Using similar epicyclic mechanism in each case, it models the solar and lunar theories of Hipparchos (c. 190 to after 126BC) and the planetary theory associated with Apollonios of Perga (fl. c. 230BC).

As well as providing room to model an epicycle for Venus to a sufficient scale, the large wheel can also carry wheels modelling epicycles for Mercury and the Sun, together with the trains to drive them; so I restore all three. The angular motion of each celestial body about the central axis is described by that of a pin set eccentrically in its epicycle disc. Each pin is engaged with a slotted lever fixed to one of a set of nested pipes on the central axis, through which its motion is carried up to a pointer on the upper end. A further pointer, driven directly from the large wheel, indicates the date.

A precedent for the use of pin and slotted follower is found elsewhere within the original fragments of the Antikythera Mechanism, as noted below. In my present model the central pipes are thin-walled tubes (for which those found in the aulos serve as a precedent)³⁹ with the levers and pointers soldered on. The pipes are therefore divided, with stepped couplings part-way up to transmit torque to the pointers while allowing the assembly to be taken apart. These thin-walled tubes are to be replaced by thick-walled pipes with the levers and hands fitted on to squares: an arrangement, more closely based on details found in the original, which will obviate the need to divide the pipes.

In order to demonstrate that a consistent level of astronomical sophistication can be achieved, the lunar theory of Hipparchos is also modelled. For this a small epicyclic platform is fixed to the central arbor, lying within the arbors for the epicycles for the Sun, Mercury and Venus.

The 'superior' planets, Mars, Jupiter and Saturn, with their different tropical periods, must have their epicycles carried on three separate platforms running at different speeds. These are contained in three individual assemblies, contrived in the same style as the rest and using the same repertoire of machine elements. They lie one above another, over the parts just described and under the dial. The latter must therefore stand high enough above the frame plate to make room. This presents no difficulty since there is no join between fragments A and C to establish by how far the dial was above the frame plate before the original instrument broke up.

The latch on the surviving piece of the front dial shows that the user was expected to gain access to the mechanism beneath, perhaps to set the planetary indications correctly. Taking this hint, I arranged the assemblies for the planets so that they may be lifted out of the case for resetting. It proved convenient to rely on their fit against the sides of the wooden case as a way of aligning them. If the corresponding parts of the original were similarly arranged, their loss through the decay of the case during its long immersion is easily explained.

The most obvious way of giving motion to these assemblies for the superior planets is to transmit it through a side arbor from the large wheel in fragment A below. I interpret two small bars, seen at about the 'seven o'clock' position from the centre of the wheel in fragment A (Fig. 2*a*), as provision for the lower bearing of such an arbor, which confirms the existence of further mechanism driven in this way. This is, therefore, evidence that supports my reconstruction of the instrument as a planetarium.

EVIDENCE FOR ALTERATION

The instrument appears to have been altered after its initial manufacture.⁴⁰ The most obvious of several indicative features is the stepped form of the wooden case (Fig. 1*a*): a design that follows inevitably from the detail of the remaining traces of woodwork but one which has the air of having been improvised. It suggests that the front part of the instrument – comprising the front dial, the internal frame plate and the mechanism between them – was designed and built, neatly contained in the smaller part of the case, without the present back dial; and that the case was subsequently extended to enclose the back dial. One would expect a new dial, made specifically for the instrument, to have been designed to fit the dimensions of the existing case. The back dial could not be fitted without altering the case and was, therefore, probably made for some other instrument. The Antikythera Mechanism as we have it appears to be a ‘marriage’.

This hypothesis explains some odd internal features, most especially a redundant set of gear teeth cut on the edge of the epicyclic platform (Fig. 2*b*). Certainly some alteration has taken place here. The probable count of 223 teeth in this wheel suggests a connection with the 223-month eclipse period-relation, and so a possible relevance to the lower back dial display. It may be a relic of an earlier gear train, perhaps part of the gearing previously fitted behind the back dial in its earlier existence as a separate instrument.

A further remarkable feature is the arrangement of the two epicyclic wheels planted on the large wheel that has just been discussed. These lie face-to-face but turn about separate centres, coupled by a pin projecting from the face of the lower wheel into a radial slot in the upper one.⁴¹ The loss of material due to damage has left the slot in the upper wheel open-ended, so that it was wrongly identified by Price as evidence of a repair. The ensemble introduces a fluctuation into the velocity-ratio of the train which serves no useful purpose in the present context. Its redundancy suggests that this is a further element from another mechanism, reused in a way for which it was not originally intended. The question arises as to whether the epicyclic platform with the paired wheels planted on it once formed an ensemble in some other design, or whether we have here elements taken from two separate designs, brought together in the realisation of a third. In any case the presence here of the pin-and-slotted-follower ensemble has an immediate significance, in providing the necessary precedent for its use with each of the restored epicyclic motions under the front dial.

CONCLUSION

Apart from its relevance to the reconstruction of the epicyclic assemblies under the front dial, the discovery of the kinematic ensemble of driving pin and slotted follower in this instrument of the first century BC is an important addition to our knowledge of the history of technology. Previously, this combination was thought to appear for the first time in a book written in 1204 or 1206.⁴²

In considering an incomplete historical artefact one should give due weight to a ‘minimal’ reconstruction: one to which as little as possible is added in accounting for the extant evidence. Price’s reconstruction of the Antikythera Mechanism appeared minimal, but it is damned by his misinterpretation of the internal arrangement and his imposition of wishful-thinking in conflict with observable detail. With our new understanding of the

internal mechanical arrangement, of the design and functions of the two back dials, of the Moon-phase display, and of the significance of the evidence of further, lost epicyclic mechanism under the front dial, we may consider a more satisfactory minimal reconstruction.

In this reconstruction the front dial would offer indications of the places of the Sun and Moon and of the day of the year. Thus far, it would resemble Price's reconstruction, but with the addition of the central display showing the phase of the Moon. There would also have to be a further complication to account for the lost epicyclic mechanism: either a modification of the mean motion of the Sun (probably according to the solar theory of Hipparchos), or a display of the motion of one of the inferior planets (probably Venus). If no further planets were shown, then some other explanation would have to be found for the feature that I interpret as provision for a side arbor to carry motion up to further mechanism associated with this dial. The upper back dial would display the relationship between synodic months and years and the nineteen- and seventy-six-year cycles connecting them. According to my conjectural reconstruction the lower back dial would show the draconitic month subdivided into half-days, and the spiral slots running along the scales of the upper and lower dials would be fitted with moveable markers.

In a material sense this would be an acceptable minimal reconstruction; but it would still offer only rather simple and oddly selective indications, contrasting incongruously with the device's considerable internal complication and the human impulse to make any instrument as comprehensive as possible. Moreover (for what it may be worth) no written record of just such an instrument is known.

The literature does, however, bear witness to the making of planetaria, and encourages us to interpret the traces of lost mechanism under the front dial accordingly, as parts of a planetarium display. Having devised one epicyclic movement, the designer could not have overlooked the possibility of repeating it as many times as he wished. I have shown that just such a full set of planetarium indications is practicable, and is compatible both with the evidence of the original fragments and with what we know of the astronomy of the time. Formal uses may be suggested for this more elaborate instrument. The ancient literary accounts assembled by Price suggest use for philosophical study, educational demonstration, intellectual entertainment, and the prediction of notable astronomical events such as eclipses. Another use is suggested by the rise in interest in personal horoscopy during the first century BC.⁴³ In order to cast an individual's horoscope the astrologer had to know the places of the Sun, Moon and all the planets at the moment of birth. Archaeological evidence, comprising many such listings on slips of papyrus, suggests that this data was commonly derived from written tables. It is however reasonable to suppose that a planetarium instrument might have been used instead, if it were available. In any case, the evident enthusiasm of a variety of present-day spectators to whom I have demonstrated my model, echoing that of Cicero in the first century BC, shows that the instrument's value as an intellectual entertainment alone probably provided a sufficient incentive for its design and construction.

Price encouraged us to think of the Antikythera Mechanism, and the astronomical instruments alluded to in literature, in the same context. We may now go further. The sophistication of what survives of the Antikythera Mechanism, and the facility with which an extended reconstruction of it as a planetarium may be devised and made to work, suggests that it was indeed a planetarium. By the same token, the instruments to which ancient

authors refer, in a manner suggesting that they were well known to their readership, might have approached the Antikythera Mechanism in their degree of mechanical complexity: ancient planetaria were probably neither as rare nor as naive as many scholars have supposed. If the Antikythera Mechanism is a solitary surviving example of the genre, that is because it alone chanced to be lost in antiquity out of reach of the scrap-metal man, to be discovered and recognised in modern times. The uniqueness of its survival is not evidence of its uniqueness in the milieu in which it was designed and made. Moreover, the fact that this instrument has been altered, and is the outcome of the marriage of pre-existing instruments, provides evidence that it comes from a workshop tradition within which a range of comparable instruments was made. Our perception of Hellenistic culture must encompass both the degree of technical attainment to which the Antikythera Mechanism bears witness, and the fact that affluent members of society must have been willing to patronise workshops which could make such things. That enlarged historical perception is even more valuable to us than the specific detail of this one surviving instrument.

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- XII. M. T. Wright: 'Understanding the Antikythera Mechanism', Proc. Conf. on Ancient Greek Technology, TEE Athens, Greece, 2006, 49–60.

NOTES

1. The authors of one compilation offer dates in the range *c.* 80–50BC, based on the study of various items of cargo (G. D. Weinberg (ed.): 'The Antikythera shipwreck reconsidered', *Transactions of the American Philosophical Society*, 1965, **55**, 3). Bol suggests a date within the decade 100–90BC for the marble sculptures (P. C. Bol: *Die Skulpturen des Schiffsfundes von Antikythera*, 1972, Berlin, Gebr. Mann Verlag). Silver coins originating from Pergamon, recovered more recently by Jacques Cousteau, are dated to 86BC (*The Cousteau Odyssey: Diving for Roman Plunder*, Warner Brothers Home Video PES34045, 1976).
2. I. N. Svoronos: *The National Museum in Athens*, 1903, Athens (in Greek); subsequently published in German as J. N. Svoronos: *Das Athener Nationalmuseum*, 1908, Athens, Beck & Barth.
3. D. J. de S. Price: 'Gears from the Greeks', *Transactions of the American Philosophical Society*, 1974, **64**, 7; reprinted as D. J. de S. Price: *Gears from the Greeks*, 1975, New York, NY, Science History Publications.
4. Price mentioned the possibility that the instrument might have been driven by a water-clock or other self-moving device, but preferred the more sober suggestion that it was worked by hand.
5. The synodic month is the period from New Moon to New Moon.
6. MTW II. (Citations in this form refer to my previous papers on this subject, collected in a numbered sequence in the Bibliography above.)
7. For example, see the review of Price's paper, R. Mercier: 'The Antikythera Mechanism', *Journal for the History of Astronomy*, 1977, **8**, 143–145; and the obituary of Price by G. L'E. Turner: *Annals of Science*, 1984, **41**, 105–107.
8. J. V. Field and M. T. Wright: 'Gears from the Byzantines: a portable sundial with calendrical gearing', *Annals of Science*, 1985, **42**, 87–138.
9. Allan George Bromley, 1947–2002, latterly Associate Professor, Basser Department of Computer Science, University of Sydney, Australia.
10. Our first findings were published as A. G. Bromley: 'Observations of the Antikythera Mechanism', *Antiquarian Horology*, 1990, **18**, 641–652. A full account of the rest of this material by the present author is currently in preparation.
11. MTW I.
12. Resolution in depth is now achieved more conveniently, although at much higher cost, by using computer-aided tomography (CAT), and the resulting images are easier for the untrained observer to comprehend; but such apparatus was then a novelty and its use was not available to us.
13. See www.antikythera-mechanism.gr.
14. For the method of estimating the numbers of teeth, see MTW VII. The results of the survey are reported in MTW VIII.
15. Arbor denotes a rotating member to which wheels, etc. are fixed. The more familiar near-synonyms, axle, shaft and spindle, connote to the mechanic the bearing of a load, a heavy component and rapid rotation, respectively.
16. The Egyptian calendar, favoured by astronomers because it was more stable and predictable than the lunar and luni-solar calendars otherwise used in the Greek-speaking world, comprised a year of 365 days divided into twelve months of thirty days each and a group of five 'epagomenal' (extra) days.
17. A contrate wheel is a gear wheel with the teeth projecting axially from one face.
18. Its correct interpretation is discussed in MTW XI.
19. The epigraphist's report is still awaited.
20. A reverted train is turned back so that its ends connect concentric mobiles. The commonest example is the set of gears connecting the hour and minute hands of a conventional clock or watch dial.

21. This period-relation, commonly associated in modern literature with the Greek astronomer Meton (fl. 432BC), was widely known in antiquity (O. Neugebauer: *A History of Ancient Mathematical Astronomy*, 1975, Berlin, Springer).
22. MTW II.
23. Within his 1974 paper (see Note 3), Price contradicted himself on this point.
24. I have so far had no access to the recently found fragment F.
25. D. J. de S. Price: 'Gears from the Greeks', pp. 46ff (see Note 3).
26. For analysis of the sections of dial in fragments A and B, see MTW VII.
27. MTW X.
28. Kallippos was interested in the commensurability of year, synodic month, and day, and pointed out that, to a good approximation, seventy-six years equals 940 synodic months or 27 759 days (O. Neugebauer: *A History of Ancient Mathematical Astronomy* (see Note 21)).
29. The subsequent use of the Kallippic Period of seventy-six years as a convenient measure of time is found in *The Almagest*, Book III (passim). See G. J. Toomer: *Ptolemy's Almagest*, 1984, London, Duckworth.
30. Saros, a misnomer originated by Edmund Halley, is the common modern term for the cycle of 223 synodic months, widely recognised in antiquity, after which the pattern of eclipses repeats with few variations.
31. D. J. de S. Price: 'Gears from the Greeks', Figs. 36, 39*a* and 39*b*, and p. 50 (see Note 3). From my own inspection of the original, I do not share Price's doubt in reading the number 223.
32. For discussion of the lower back dial and the train serving it, see MTW VI and MTW IX.
33. The plane of the Moon's orbit changes continually so that the nodes, defined by its line of intersection with the Ecliptic, move round slowly in relation to the background of stars in a direction opposite to that in which the Moon moves. Consequently the draconitic month is short.
34. MTW XI.
35. The reconstruction is developed in MTW IV and MTW V. A first attempt at modelling the planetarium display is discussed and illustrated in MTW III.
36. Since the Earth's orbit is elliptical, and its angular velocity about the Sun is subject to Kepler's Area Law, the apparent motion of the Sun in relation to the stars is not uniform through the year.
37. In the geocentric system a planet is termed inferior or superior depending on whether it is supposed to lie below or above the Sun. From the heliocentric standpoint, the inferior planets lie within the Earth's orbit while the superior planets lie outside it. In contrast to the observed behaviour of the inferior planets, the superior planets may be seen at any angular separation from the Sun.
38. D. J. de S. Price: 'Gears from the Greeks', pp. 47 (Fig. 36) and 50 (see Note 3).
39. The aulos was a common ancient reed instrument. Its body was regularly made of lengths of hollow bone fitted within a thin-walled bronze tube. In some elaborate models there were outer bronze sleeves controlling side-holes, which had therefore to move on the inner sleeve but still make an airtight joint.
40. A first discussion of the evidence for alteration may be found in MTW XII. The question is pursued further in another paper, now in preparation.
41. This feature is discussed and illustrated in MTW VII and again in MTW IX.
42. Ibn al-Razzaz al-Jazari: *The Book of Knowledge of Ingenious Mechanical Devices*, (trans. D. R. Hill); 1974, Dordrecht, Reidel.
43. A. Jones: *Astronomical Papyri from Oxyrhynchus*, 1999, Philadelphia, PA, American Philosophical Society.

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